

Color filter for 10.4-in.- diagonal 4096-color thin-film-transistor liquid crystal displays

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Color filters with a wide color reproduction gamut and high transmittance were developed for 10.4-in.-diagonal 4096-color thin-film-transistor liquid crystal displays using pigment-dispersed photosensitive polymers. The transmission spectrum of each color pixel was designed in conjunction with other components such as backlight and polarizers in order to meet front-of-screen quality requirements. To improve screen quality, a low-resistivity common electrode was used, eliminating the top coating. A repair technique utilizing back-exposure was also developed to improve production yield. This pigment-dispersed-type color filter has the merits of a simple process, low fabrication cost, good uniformity, high reliability, and applicability to high-resolution displays. There is a problem involving deterioration of contrast ratio caused

by the depolarization effect of the color filter. We measured depolarization factors for several pigments and showed that the yellow pigment was the major contributor. This depolarization effect has been minimized.

Introduction

There are two ways to define front-of-screen (FOS) quality in liquid crystal displays (LCDs). One is evaluation by human eyes on the basis of human factors such as screen quality (flicker, etc.). Another is measurement by optical analyzers such as brightness or chromaticity. In display products, all of the FOS quality factors are important. The color filter (CF) is one of the key components because it directly defines FOS quality.

Several technologies for CF fabrication have been proposed, including gelatin, electrodeposition, printing, and dispersed pigment. These technologies have already

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Table 1 Influence of cell and color filter parameters on front-of-screen quality.

<i>Front-of-screen quality factors</i>	<i>Influenced by</i>	<i>Controlling color filter parameters</i>
Luminance	Light transmission fraction of pixel Transmission of cell Luminance of backlight Transmission of color filter	Black matrix: Optical density Pattern accuracy Thickness
Chromaticity	Transmission spectrum of color filter Emission spectrum of backlight Transmission spectrum of cell	Color filter: Transmission spectrum Depolarization Thickness
Contrast	Electrical characteristics of transistor Thickness of cell Reverse tilt in cell Depolarization in color filter Optical density of black matrix	Common electrode: Resistivity Thickness
Crosstalk	Electrical characteristics of transistor Resistivity of color filter electrode	

been used commercially in the pocket TV market, but they present some problems for large, high-resolution, full-color thin-film-transistor (TFT) LCDs.

The dyed-gelatin CF offers high transmittance and good color purity [1], but also has the following disadvantages. CF reliability, especially resistance to heat and ultraviolet rays, is poor. The fabrication process has many steps, and its process conditions must be tightly controlled. Gelatin contains metal ions which diffuse and alter the transistor characteristics, and requires application of a protective layer on the gelatin to prevent this diffusion.

The electrodeposition method has a simple process [3], but this method has problems of low yield and restriction of color arrangement because it requires pixel-size electrode patterning for electrodeposition.

In the printing method, the process is simple [4], but a polishing process is required in order to obtain flatness. Its uniformity is not good, and fine patterning is difficult. Filtering of ink for removing foreign particles is hard because the ink for printing has a high viscosity.

Pigment-dispersed color filters have high reliability and high color purity [2]; they can be finely patterned, and the process comprises fewer steps.

Of these methods, the dispersion method combines the merits of simple process, low cost, uniformity, high reliability, and fine resolution. A CF for 10.4-in.-diagonal 4096-color TFT LCDs using pigment-dispersed photosensitive polymers has been developed from FOS quality requirements by optimizing the CF design and incorporating it in the display structure.

Optimization and fabrication of pigment-type color filter

• Overall requirements

LCD front-of-screen quality includes brightness, chromaticity, contrast ratio (CR), and screen qualities such as crosstalk and flicker. The color filter should be designed to meet the FOS quality requirements on the basis of the combined characteristics of all the components: glass substrate, CF, polarizer, liquid crystal (LC), thin films on the TFT, and backlight (BL).

Table 1 shows the influence on FOS quality of the color filter together with the other components. Each factor of FOS quality is determined by these LCD components, especially BL and CF, which are the most effective and controllable factors. Among the FOS quality requirements, higher contrast ratio and minimum crosstalk result in better screen quality, and the specifications of brightness and chromaticity are given from the viewpoint of a comparison with the cathode ray tube (CRT). A higher CF transmittance also results in lower power consumption. The CF and BL spectra are designed to realize the same color as the CRT for the chromaticity of red, green, blue, and white balance, together with the highest possible FOS brightness.

• Spectrum design

The chromaticity of liquid crystal displays should be comparable to that of the CRT. The target of the chromaticity design was to approach the specifications as closely as possible with the actual panel by independently adjusting the color filter and backlight characteristics.

The LCD chromaticity was calculated by multiplying together three spectra (the BL spectrum, the CF spectrum, and the monochrome panel spectrum).

The BL emission spectrum was calculated by multiplying the fluorescent lamp (FL) spectrum by the transmission spectrum of the diffuser. The FL contains red, green, and blue phosphor, so the BL emission spectrum was determined from the phosphor mixture. Then the CF transmission spectrum was calculated from red, green, blue, cyan, violet, yellow, and black pigment spectra, and was determined from the mixture of those pigments. Table 2 lists the pigments utilized in an actual display which have high heat-resisting properties, high clarity, and high color purity.

The monochrome panel transmission spectrum was actually measured on the LCD without CF and BL. It was dealt with as a constant on the LCD chromaticity calculation.

The LCD chromaticity, which had two parameters, the mixture of phosphors in BL and the mixture of pigments in CF, was calculated and compared to the chromaticity specification. Iteration was done using the method of nonlinear least squares to obtain convergence for the four chromaticity components—red, green, blue, and white balance.

• Optimal thickness of the common electrode

Indium tin oxide (ITO) sputtered on CF (Figure 1) not only has a role as the common electrode, but also is a significant parameter which influences cell transmission. Cell transmission of the OFF state in the normally white mode changes with the thickness of the ITO (Figure 2). Because there are no ITO film thicknesses which maximize the brightness of red, green, and blue at the same time in the combined structure of the CF and the ITO film, we chose the thickness of 1500 Å, which maximizes the white brightness. The resistance of this optimized thickness is acceptable as a common electrode and satisfies the CF specification.

• Color filters for 4096-color thin-film-transistor liquid crystal displays

The structure and characteristics of the prototype CF are shown in Table 3. The black matrix has a two-layer structure. The thickness of the color resist layer was 2 µm, and the difference in the thicknesses of the red, green, and blue pixels (flatness) was less than 0.1 µm. There was no top coat, and diagonal resistance was 70 Ω. Optically, a 20.8% transmittance and 72.8% color reproduction gamut of the National Television Standard Committee (NTSC) standard, as displayed in the chromaticity diagram recommended by the Commission Internationale de l'Eclairage (CIE) in 1931 was obtained and is shown in Figure 3.

Discussion

• Reduction of the display crosstalk effect

Larger, higher-resolution, full-color displays present new problems of poor luminous uniformity and a horizontal line seen on the extension of the displayed pattern edge (crosstalk) which have not been seen before. The primary cause of these problems is the shift of the transmittance vs. voltage (T-V) characteristics curve. The T-V characteristics express the relation between the voltage applied to the LC and the transmittance of the LC cell. The most effective remedy for this problem is to lower the resistance of the common electrode.

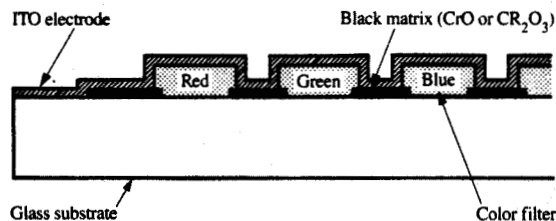


Figure 1

Cross section of color filter without topcoat.

Table 2 Organic pigments selected for the 4096-color display.

Color	Pigment
Red	4,4'-Bis(1-amino-9,10-anthraquinone)
Green	Cu-Hexadecachloro-phthalocyanine
Blue	Cu-Phthalocyanine
Yellow	Isoindoline compound
Violet	Dioxazine compound

Table 3 Prototype color filter specifications and characteristics.

Structure	BM	Layer structure of Cr ₂ O ₃ and Cr
	Thickness	2 µm (R, G, B)
	Thickness variation	<0.1 µm
	Top coat	None
	ITO	1500 Å, 30 Ω/□
	Diagonal resistance	70 Ω
Characteristics	Transmittance	20.8%
	NTSC gamut	72.8%

The resistivity can be lowered by heat treatment, but there are limits to this process because the CF has poor heat resistance. The lowest resistance of the common electrode was obtained by making contact between the ITO and the conductive black matrix (BM) on the CF substrate without top coat (Figure 2). A low diagonal resistance of 70 Ω was obtained by sputtering the ITO (1500 Å), which had a sheet resistance of 30 Ω/□. Crosstalk was then reduced to acceptable values.

We adopted a two-layer structure of chromium and chromium oxide as BM material, so the FOS quality relating to glare was considerably improved because the reflectance of this BM material was lower than that of the simple chromium layer structure.

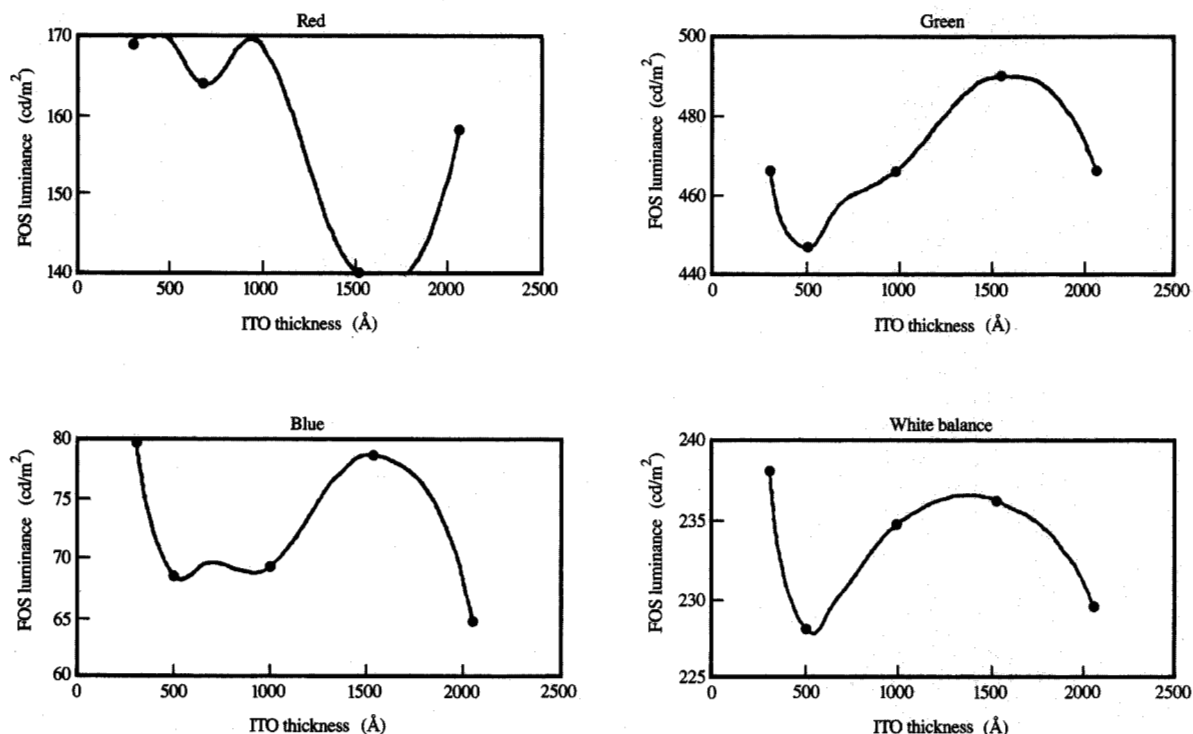


Figure 2

FOS luminance vs. indium tin oxide thickness. (Backlight brightness = 2330 cd/m^2 ; color temperature = 7466 K; aperture ratio = 100%.)

Figure 4 shows the results of the bias temperature humidity (BTH) stress test of the LCD with this CF. The BTH stress test is an accelerated life test in which the product is exposed to high temperature and high humidity; it is one of the reliability tests required by the product specification.

It is seen that there is no difference in decay of charge retention (voltage storage ratio) between the CF with and without top-coat layer; thus, eliminating the top coat raises no problems of reliability. In addition, eliminating the topcoat layer provides cost benefits. If the BM is expanded to the part of the transfer area where contact is made between the common electrode on the CF substrate and the TFT array substrate, the resistance of the common electrode is expected to be even lower.

• *Repair technique for pigment-type color filter*

Since the material of the CF is a negative-type photoresist, foreign particles on the photo mask during the photo process cause defects within a color pixel, because the particles disturb exposure and the photoresist is not

polymerized. These defects become white defects when viewed by eye, because the brightness of a pixel with this defect is greater than the brightness of normal pixels.

To repair the white defect, the color resist having the pixel color pigment with the defect was coated on the CF. This color resist was then exposed from the rear side. The proper energy of exposure photopolymerizes the coated color resist on the defect part where the light exposes directly. On the normal pixels, the color resist is not photopolymerized, because the light energy is decreased by passing through the CF. Transmission spectra and spectral sensitivities of color resists, as well as the emission spectrum of the ultra-high-pressure mercury light used in this exposure, are shown in **Figure 5**. This shows that the transmittances of each color at peaks of the light source in the photosensitive region of the color resist are low enough to decrease the exposure energy on normal pixels. After development, the color resist on the part with the defect remains, and the defect is repaired.

Figure 6 shows the relation between the exposure energy and the transmission of each normal color pixel after

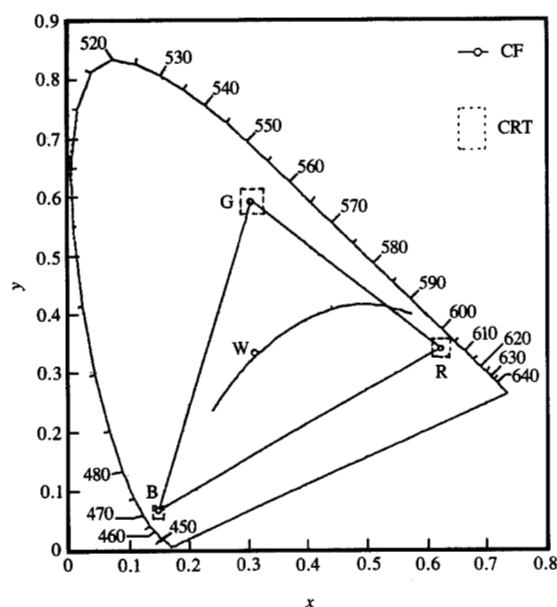


Figure 3

CIE 1931 chromaticities of blue (B), green (G), red (R), and white balance (W) of the color filter. (The curve shows black-body radiation.)

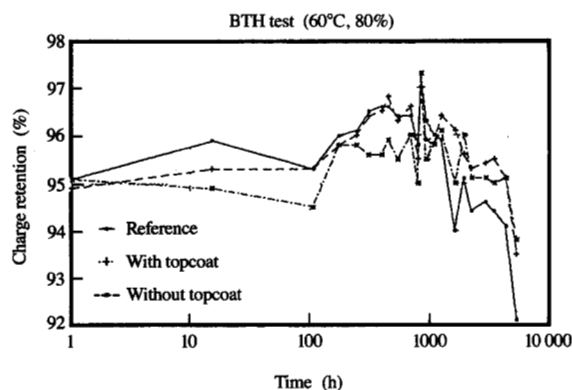


Figure 4

Bias temperature humidity stress test of LCD.

repair. If the exposure energy is too strong, the transmittance of normal pixels decreases, because the color resist applied for repair photopolymerizes on normal pixels and remains after development. Since the color

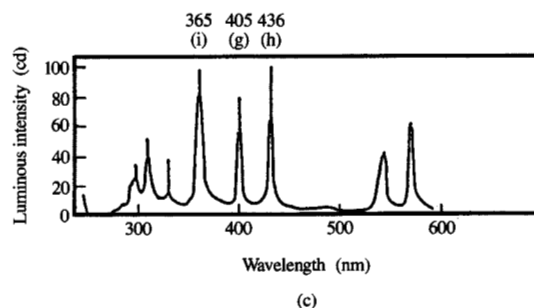
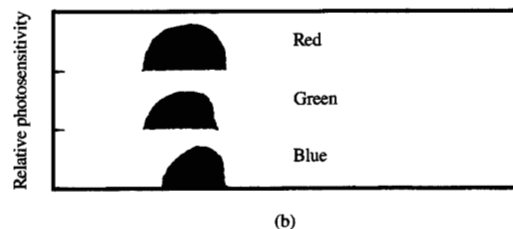
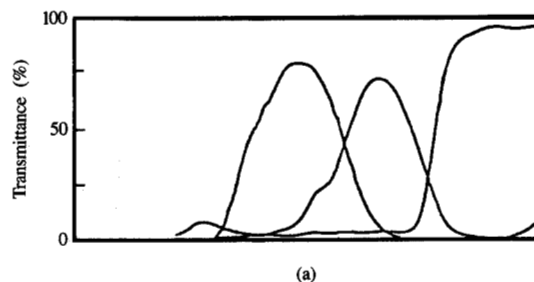


Figure 5

(a) Transmission spectrum of color filter; (b) spectral sensitivities of color resist; (c) source spectrum of very high-pressure mercury light.

resist on normal pixels must be completely removed, the exposure energy for repair must be smaller than threshold energies of color resist on normal pixels. The proper exposure energy was chosen to be 5 mJ/cm^2 , because threshold exposure energies of color resist on normal red, green, and blue pixels were measured to be 5 mJ/cm^2 , 80 mJ/cm^2 , and $>100 \text{ mJ/cm}^2$, respectively.

• Depolarization effect of pigment-type color filter

Figure 7 shows angular dependencies of the contrast ratios of LCDs. The range of contrast ratio over 50, which is a FOS requirement, is almost equal in both LCDs. For higher FOS quality, the contrast ratio must be higher, but

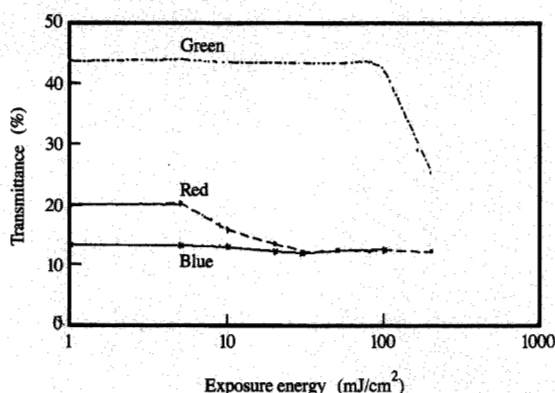


Figure 6

Relation between the exposure energy and the transmission of CF.

absolute values of the contrast ratios of LCDs with pigment-type CFs are lower than those of LCDs with dye-type CFs.

Figure 8 shows normalized contrast ratios calculated from the measured brightness of color filters fabricated by several methods and placed between parallel and crossed polarizers. Samples of the CF contain two types of colorants and were produced by four types of fabrication methods. The contrast ratio of dye-type CFs is nearly equal to that of polarizers alone, but the contrast ratio of

pigment-type CFs is much lower compared to that of polarizers and also the dye-type CFs. This means that the incident light polarized by the first polarizer is depolarized by passing through the pigment-type CF. A reason for the contrast ratio degradation is light leakage when black is displayed. The mechanism of light leakage by depolarization is shown in Figure 9.

Figure 10 shows the depolarization parameter for each color of the pigment-type CF. This parameter is defined by the ratio of two contrast ratios: One is calculated from the two brightnesses measured in an arrangement in which the CF is placed between two parallel or crossed polarizers, and the other is calculated from brightnesses measured in an arrangement in which the CF is removed from the polarizers. The depolarization of red and green is stronger than that of blue. Each red and green resist contains not only each primary pigment but also yellow pigment for color matching. The depolarization parameter for each primary pigment color is shown in Figure 11. This shows that the yellow pigment causes stronger depolarization than the other pigments.

Figure 12 shows the relation between the contrast ratio of the yellow CF and the size of the yellow pigments in the CF. The contrast ratio becomes higher with smaller pigment size. One can infer the causes of depolarization by the pigment-type CF to be scattering and birefringence. The exact relation between depolarization and scattering or birefringence is not understood quantitatively, but the contrast ratio of the pigment-type CF has been improved in several ways, including selection of pigment, optimization of pigment size, and improvement of pigment dispersion.

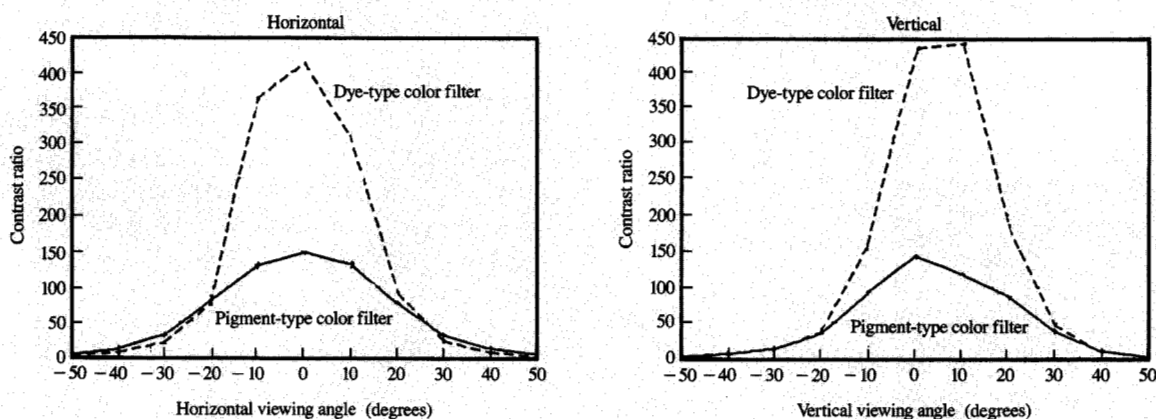


Figure 7

Angular dependences of the LCD contrast ratios.

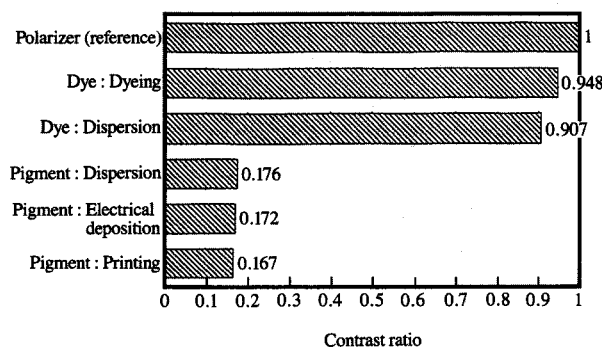


Figure 8

Contrast ratio for each CF fabrication method.

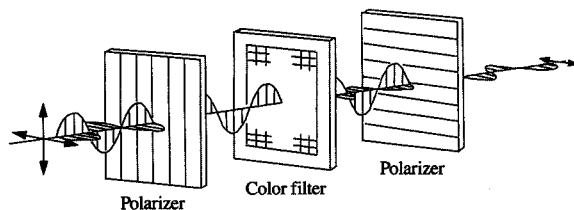


Figure 9

Mechanism of light leakage by depolarization.

Conclusion

The color filter is one of the key components of TFT LCDs; the one described here achieves high FOS quality. The spectrum of the CF was designed by color-matching simulation to achieve the required performance. The ITO thickness of the common electrode was set to the optimum value for LCD light transmission.

Crosstalk was minimized by lowering the resistance of the common electrode; this was achieved by making contacts between the ITO and the conducting black matrix. The pigment-dispersed photoresist adopted for the CF material offered many advantages such as simple process, eventual low fabrication cost, good uniformity, high reliability, and fine patterning. Its one weak point was that the contrast ratio decreases, a common problem of other CF fabrication methods using pigments, such as the printing method and the electrodeposition method. The

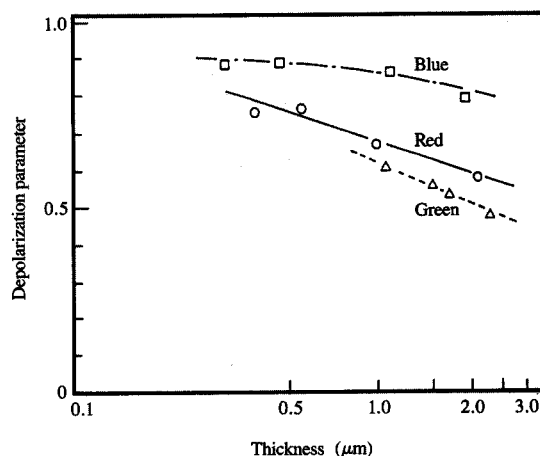


Figure 10

Depolarization parameter for each color of pigment-type CF.

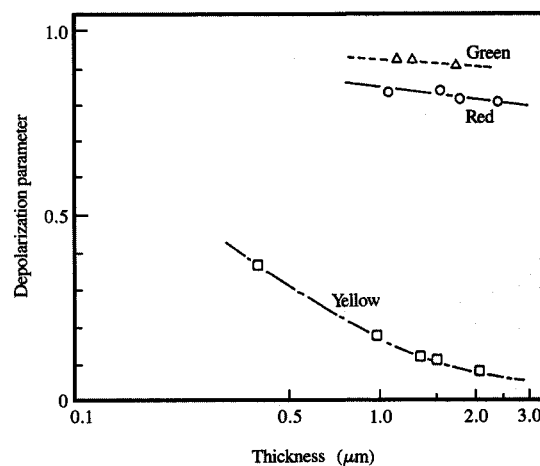


Figure 11

Depolarization parameter for each primary pigment color.

cause of this depolarization was considered to be scattering and birefringence, and the yellow pigment was the major contributor. Selection of the proper yellow pigment, optimization of pigment size, and improvement of pigment dispersion improved the contrast ratio sufficiently that this color filter offers adequate quality for a 10.4-in.-diagonal 4096-color TFT LCD.

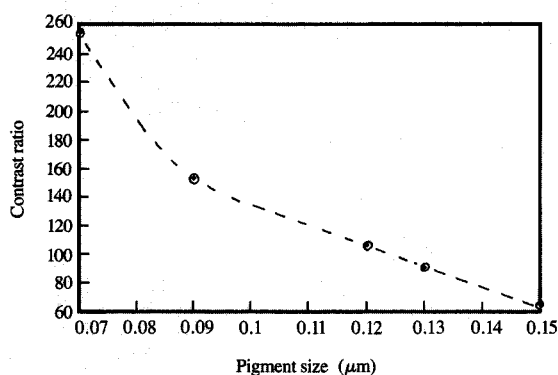


Figure 12

Contrast ratio of yellow filter vs. pigment size.

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